

Rainfall Components: Variability and Spatial Distribution in a Mediterranean Area (Valencia Region)

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ABSTRACT

In the last half of the twentieth century, the precipitation regime on the Spanish east coast showed an overall pattern of reduction in precipitation totals. This work presents the results from a novel procedure to disaggregate the precipitation series in the Valencia region on the basis of their meteorological origin. Important differences are found between specific trends and changes in the contributions from 1) Atlantic frontal systems, 2) convective–orographic storms, and 3) easterly advections over the Mediterranean Sea (backdoor cold fronts). The series for the three components are then used to analyze the evolution, variability, and spatial distribution of the region's rainfall and to determine the correlations with the North Atlantic Oscillation (NAO) index. The results establish significant differences between inland areas, with a trend toward decreasing precipitation and thus increasing aridity, and coastal areas, with increasing precipitation that tends to be progressively more torrential in nature. Likewise, the correlations with the NAO index also change and show opposite signs for the different components.

1. Introduction

a. Background

Climate variability, especially in relation to global change, monopolized the interest of many climatologists in the last decades of the twentieth century. But in spite of the numerous studies published, some questions are still pending in-depth analysis. This is largely due to the difficulty of connecting the variations observed in specific climate parameters to a generalized climate change. Available studies on seasonal and annual precipitation and their trends at local and global scales show important variations from one area to another are. Thus, whereas it is possible to speak in general of a positive precipitation trend for northern Europe, the trend is clearly negative for the countries in southern Europe (Houghton et al. 1996, 2001; Schönwiese and Rapp 1997).

Works by Brizio and Mercalli (1992), Lamarque and Jourdain (1994), Quereda et al. (1996), Di Napoli and Mercalli (1996), Buffoni et al. (1998, 1999), and Bru-

netti et al. (2001) seem to confirm a northerly displacement of the Mediterranean front, resulting in a negative precipitation trend south of the 40°N parallel. This statistical generalization supports the general concept of a rainfall reduction in the Mediterranean basin from the last third of the twentieth century, and similar conclusions have been derived from the analysis of larger-scale climatic phenomena, that is, the El Niño–Southern Oscillation (ENSO; Mariotti et al. 2002b), and the North Atlantic Oscillation (NAO; Hurrell 1995; Marshall et al. 2001; Mariotti et al. 2002a).

Studies specific to the Iberian Peninsula suggest precipitation reductions in its southern half, which become increasingly more pronounced southward and eastward (Sales Martínez et al. 1982; Raso Nadal 1996; Montón and Quereda 1997; Martín Vide 1987). Other studies do not show a clearly marked trend in the evolution of precipitation totals for the whole of Spain but do show a noticeable increase in interannual variability during the latter years of the twentieth century (Almarza 2002). Similar conclusions have been derived from analyzing the reconstructed precipitation series from 1864 to the present for eastern and southeastern Spain (Chazarra and Almarza 2002). Finally, recent studies on the Spanish east coast (Peñarrocha et al. 2002) show an increase in both the number of torrential events and their precipitated amounts.

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The implication of all these observations is that the variations in precipitation totals could be related to changes in event type, in frequency, and in precipitation intensity by event and/or in any combination of these. Thus, we asked the following questions: 1) could the increases in interannual variability or the trends in precipitation totals, or both, mask changes in the partitioning of the precipitation totals with respect to the meteorological situations producing them, and 2) could these changes also include important regional variations and seasonal differences between the specific tendencies in each region?

b. This study

This work attempts to answer the aforementioned questions for the Valencia region of Spain in the western Mediterranean. The approach has been to analyze the daily precipitation data for the period 1959–2000 in the light of the mesometeorological information obtained from various European research projects (from 1983 to present). These projects have documented the diurnal cycles of Mediterranean atmospheric processes, including their seasonal evolution and their marked orographic dependence (Millán et al. 1992, 1997). Results derived from other climatic applications of the same mesometeorological information and datasets were also used (Millán et al. 1995, 1998; Estrela et al. 2000; Pastor et al. 2001; Peñarrocha et al. 2002).

The study area and the Spanish rain regime from an orographic perspective are presented first. This is further expanded to categorize the meteorological situations that produce precipitation in the Valencia region and to select disaggregation criteria for processing the precipitation data in terms of the main synoptic types. The resulting criteria, and the weather maps for the period 1959–2000, are then used to reduce the available daily precipitation data. The series for the three precipitation types, their time evolution, and spatial patterns are analyzed and correlated with the NAO index, and the work ends with a discussion of the results.

2. The setting

a. The Iberian Peninsula

The Iberian Peninsula is the physical interface separating the central Atlantic from the Mediterranean Sea and is located approximately between 36° and 43°N. The lay of the land is illustrated in Fig. 1. The main structure consists of two high plateaus with average heights ranging from 500 to 1000 m MSL. The upper plateau is limited in the north by the Cantabrian Mountains, aligned east to west, and in the south by the Cen-

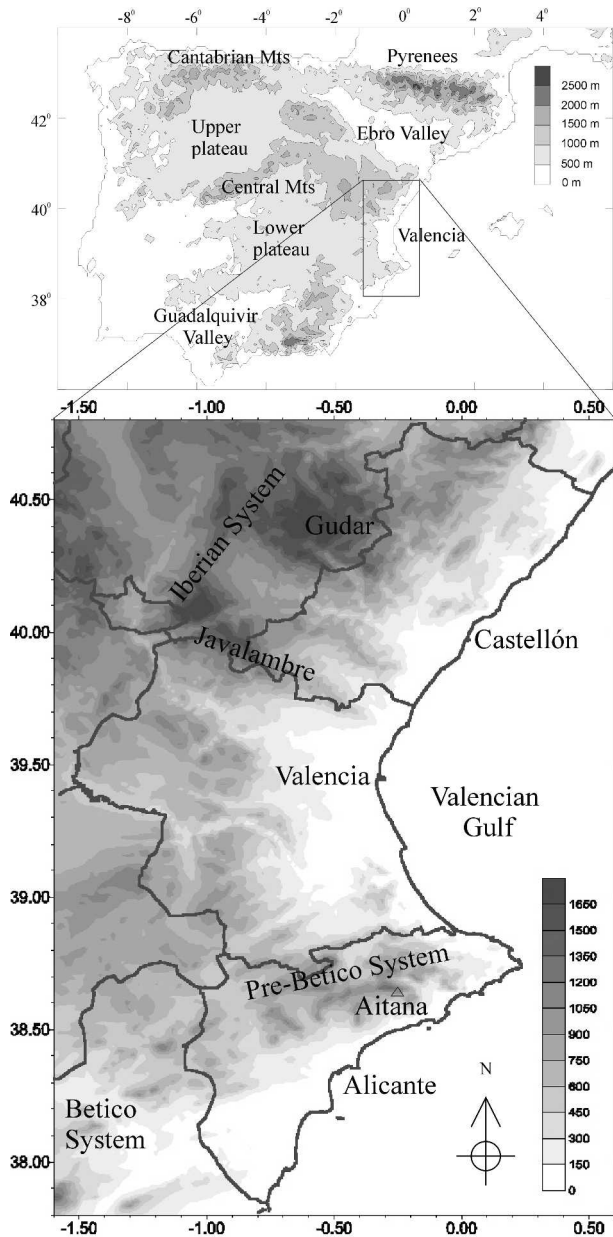


FIG. 1. The lay of the land: the Iberian Peninsula and Valencia region.

tral Mountains, which run approximately southwest to northeast and separate the two plateaus. The lower plateau has no clearly defined southern boundary and ends more or less at the edge of the Guadalquivir River valley.

The Iberica, Betica, and Penibetica Mountains constitute one of the main structures in the peninsula, that is, the Iberian Cordillera system. Together, these systems form a large arch, facing west, which stretches from the Cantabrian Mountains in the north and forms

the southwestern wall of the Ebro valley. This arch continues to the south and eventually runs west forming the southern edge of the Guadalquivir River almost to Gibraltar. The Ebro valley is an entity unto itself, providing lowland that extends almost all the way from the Mediterranean to the Atlantic at the Cantabrian Sea. It is aligned in a general northwest–southeast direction and is confined in the north by the Pyrenees Mountains.

On the northern edge of the peninsula, the coastal plains are either very narrow or nonexistent, with medium-to-large estuaries. Along the Mediterranean coast all the way to Gibraltar, the coastal plains, formed by various river flood plains, are more extensive. They tend toward the shape of an irregular triangle, and in some areas their apex can extend inland as far as 50 km from the coast. Their inland edges tend to end abruptly at the steep slopes of the coastal mountains.

Along the southwest and west coasts, the valleys show a more gradual entry into the sea, but their aspect also varies from south to north. The Guadalquivir valley is the largest and lowest valley, followed by the Guadiana and Tagus valleys, which become progressively narrower and steeper. The Duero River drains the upper plateau and drops almost directly down to the sea, and the Miño River watershed is confined within the northwestern corner of the peninsula.

b. The Valencia region

Located on the east coast of the Iberian Peninsula at about the center of the arch formed by the Iberian Cordillera system (Fig. 1), the Valencia region is characterized by very complex orography (Mateu Bellés 1982). The coast is occupied by a series of coastal plains (Rosselló Verger 1969). The high terrain in the south and southwest is formed by the Betica Mountains. Their easterly extension, that is, the Pre-Betica range, reaches directly into the sea with cliffs and ridges of more than 700 m MSL in height near the cape of San Antonio. The highest peak inland (Aitana) is 1558 m MSL. To the north and northwest are the Iberian Mountains with a high ridge (Javalambre) and extensive mesas (Gudar), both just over 2000 m MSL. Almost exactly due west of the city of Valencia, the mountains are lower, with the highest points reaching only 1100 m MSL, and they provide a direct and almost ridgeless rise from the coast to the lower plateau.

The climate of the region is semiarid with annual precipitations between 300 and 500 mm. The extreme south is more arid with precipitations below 300 mm (Peñarrocha 1990, 1994). There are two areas with annual precipitations above 800 mm. One, the “wet nucleus,” is located south of the Valencian Gulf at the extreme east end of the Pre-Betico system, and the

other is located in the upper regions of the Iberian system at the northwestern edge of the territory. Thus, from the spatial point of view, the whole area has been traditionally considered a region of well-marked climatic variations (Pérez Cueva 1994).

3. Meteorology in the Iberian Peninsula: Orographic perspective

a. Traveling depressions

The airsheds in the two plateaus are essentially open to the Atlantic and closed inland by the mountain ranges. Frontal system effects depend to a very large extent on the relative orientation of the surface flow to the orographic features. If the depression tracks lie north of the peninsula (higher than $\approx 43^\circ\text{N}$), the surface flow will converge over the northwestern quadrant of the peninsula, including the Cantabrian and Pyrenees Mountains. This results in precipitation along the north- and northwest-facing slopes and föhn-type effects on the inland-facing slopes, that is, the southern slopes and piedmont areas.

A similar situation occurs along the northern slopes of the Central Mountains with a corresponding föhn shadow along the southeastern slopes. In general, by the time these systems reach the southern half of the peninsula, there is little moisture left, and fair weather dominates. The surface flow becomes channeled along the Ebro valley, and precipitation occurs mainly on the northwest-facing slopes of the valley's southern wall. Hot and gusty föhn winds tend to dominate over the east (Mediterranean) coast.

This situation changes significantly when the depression centers approach the peninsula below approximately 40°N . Then, the main convergence takes place along the west coast and the southwest-facing slopes of the same Central Mountain chain, while föhn effects occur along the northern slopes, particularly over the northern (Atlantic) coast. Precipitation develops along most of the west-facing slopes of the Iberian and associated mountain systems, and intense föhn effects take place on the other side of these mountain chains, including all of the east coast and Ebro valley where the winds are also strongly channeled toward the Mediterranean.

Finally, when the depression tracks approach the peninsula below $\approx 37^\circ\text{N}$, all the south- and southwest-facing slopes receive rain, especially those in the southern half of the peninsula. The same occurs for the west-facing slopes of the Iberian system, in particular the ones in the Betico and Penibetico systems. Under some conditions [see section 4d(2) below], these lower-track depressions also produce some convergence along the

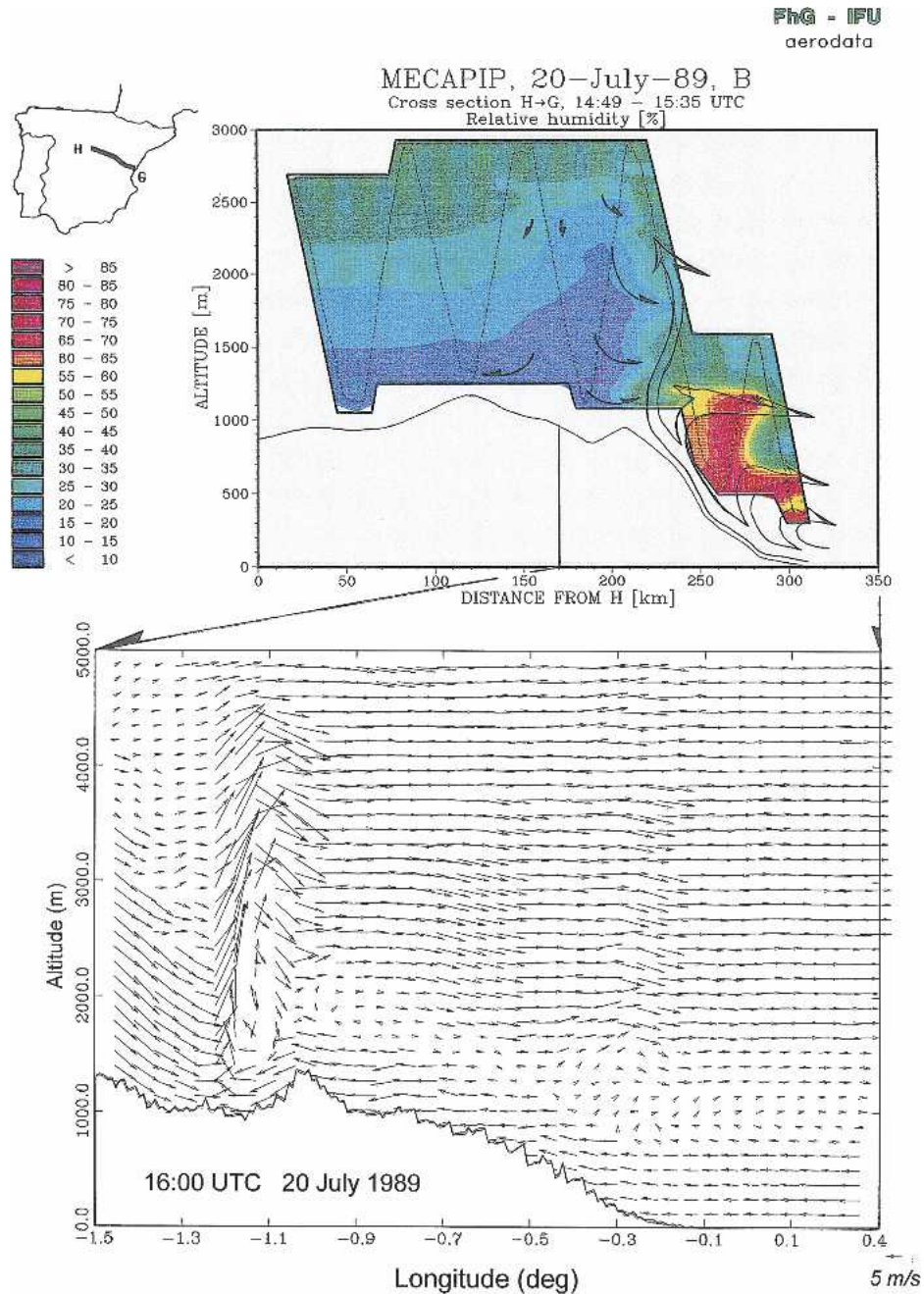


FIG. 2. (a) Penetration of the combined sea breeze and up-slope winds shown by the relative humidity measured with an instrumented aircraft. (b) Corresponding section of the wind obtained by modeling (see also Fig. 3). The vertical component of the speed has been multiplied by 10. The data and modeling results indicate that the drier air mass observed in (a) results from compensatory sinking inland of the coastal circulatory cell.

mountain chains inland from the southeast coast, causing rain over the slopes facing southeast. But, in general, the east coast tends to suffer a föhn effect with hot, gusty winds and little or no rain.

b. Late spring and summer conditions

In summer, the Iberian Peninsula becomes relatively isolated from traveling depressions and their frontal

systems. An anticyclonic ridge of high pressure becomes established over the Cantabrian Sea while mesometeorological circulations, with marked diurnal cycles, develop over the peninsula. In particular, the Iberian thermal low (ITL; Barry and Chorley 1987) develops during the day when a number of local circulations grow and merge into a self-organized circulatory system at peninsular scale.

Along the coasts, the sea breezes and upslope winds combine with their return flows aloft and their compensatory subsidence over the sea to create vertical recirculations, as shown in Fig. 2. This has been documented in several European research projects (Millán et al. 1996, 1997). The strongest local circulations develop along the Mediterranean coast because of the early onset of solar heating on its east- and south-facing slopes. These surface flows can travel distances of the order of 140–160 (+) km during the day and reach the tops of all the mountain ridges in the Iberian Cordillera system with the exception of some areas in the Ebro valley. In this context, therefore, any mountain range located less than approximately 100 km from the sea can be considered a “coastal mountain.”

Moreover, modeling with the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992) has shown (Fig. 3) that the surface flows coalesce into several convergence lines locked to some of the main orographic features. On the coastal side, these lines mark the final reach of the combined sea breeze and upslope winds. Deep orographically aided convection (up to 5 + km) takes place along these lines, even under dry conditions (Fig. 2). Of particular importance is the fact that compensatory subsidence occurs not only over the colder peripheral seas, but also over some of the inland areas surrounded by convergence lines. The point is that under strong summer insolation in semiarid terrain one would expect deep convection over these inland areas; however, as the circulations become self-organized, local convection can become confined vertically by the compensatory subsidence to the deep convective–orographic activity along the surrounding mountains.

During the late afternoon, storms tend to develop at the leading edges of the coastal circulations, that is, over the convergence lines following the ridges of the coastal mountain ranges, near the heads of the main watersheds, or even before reaching them. Afternoon–evening storms can also develop over the Central Mountains.

c. Late summer and autumn conditions

By late summer, the formation frequency of the Iberian thermal low decreases with the shorter days and coincides with the southerly displacement of the de-

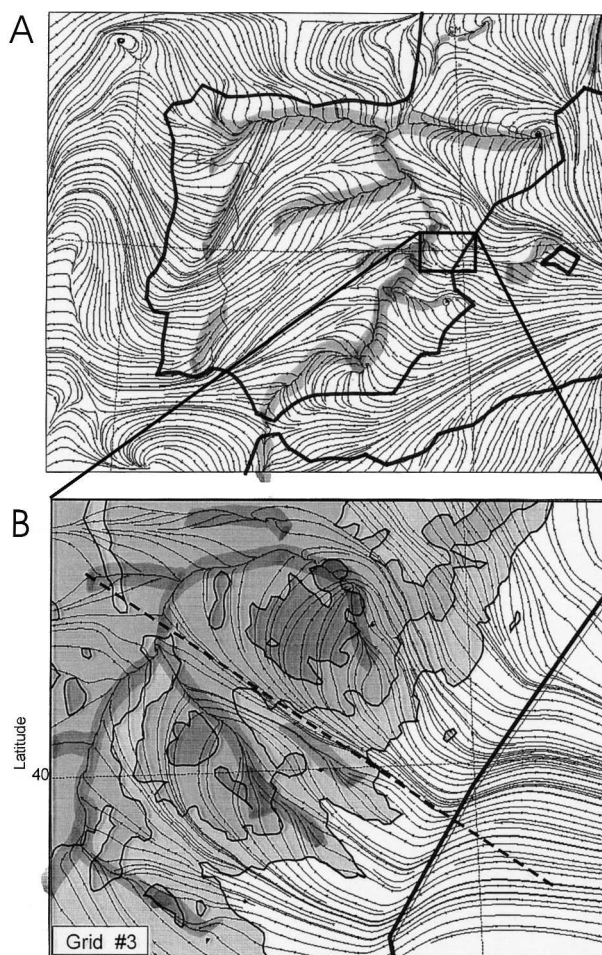


FIG. 3. Modeled surface streamlines resulting from the formation of the ITL on 20 Jul 1989: (a) for the Iberian Peninsula (10 km $\times$ 10 km grid) and (b) for the Valencia region (2 km $\times$ 2 km grid). Streamlines appear in areas inland and along the valley axes as a result of compensatory subsidence to the vertical injections along the surrounding mountain ridges. The dotted line in (b) marks the vertical plane for the airborne measurements and modeling data in Fig. 2.

pression tracks over the central Atlantic. By this time nights are longer, the European continent becomes progressively cooler, and the migration of warm-core anticyclones from the central Atlantic toward central Europe begins. By this time also, the Mediterranean Sea has reached its maximum annual temperature, and the northeasterly-to-easterly flows along the southern flanks of the migrating anticyclones begin to advect increasingly colder continental air over a much warmer Mediterranean Sea.

Under these conditions, intense instability develops over the Mediterranean Sea. This is associated with a vigorous moisture-recharge mechanism driven by the temperature differences between the sea surface and the advected air mass, and the result can be very intense

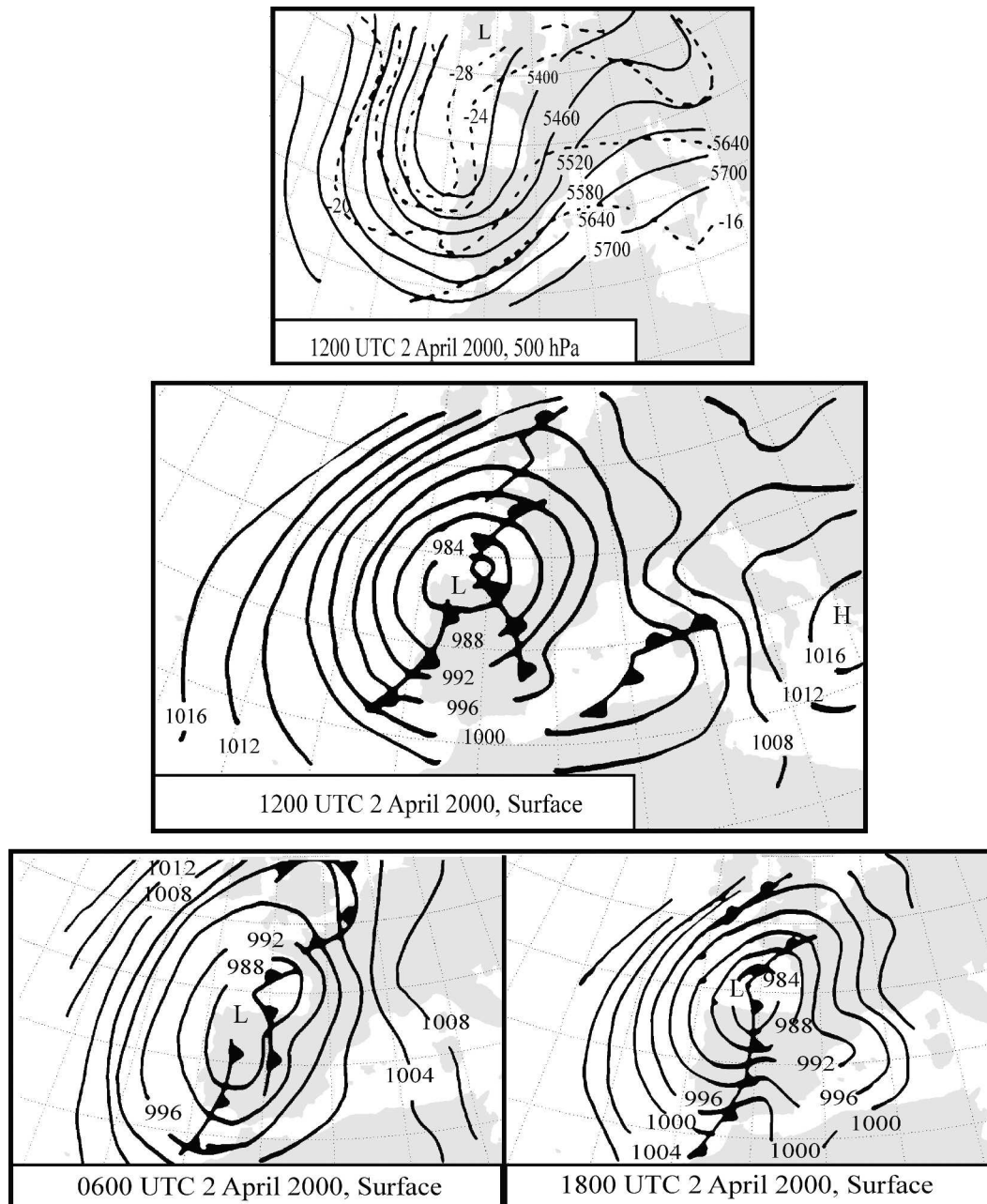


FIG. 4. Synoptic conditions typical of an Atlantic frontal system crossing the Iberian Peninsula.

precipitation events. The term Mediterranean cyclogenesis has been broadly used to describe a wide variety of processes related to these and other flows (see special issues of *Atmos. Res.*, 2001, vol. 56, no. 1–4, and 2003, vol. 67–68, special issue). In general, the area affected by precipitation at a specific time and place will depend on both the direction of the advected air mass (Meteorological Office 1962; Barry and Chorley 1987) and the distribution of the large warm water pools along its path (Millán et al. 1995).

Advections from north/northwest to north, through the Carcassonne Gap and/or the Rhône valley, reinforce the cyclogenesis to the lee of the Alps (Genoa depressions) and affect mainly Italy and parts of northern Africa (Tunisia). The Spanish Mediterranean coast and southern France are affected by flows from the northeast to the southeast. Moreover, precipitation amounts in these regions have been shown to be highly sensitive to changes in the Mediterranean sea surface temperature (Pastor et al. 2001). We consider the results of

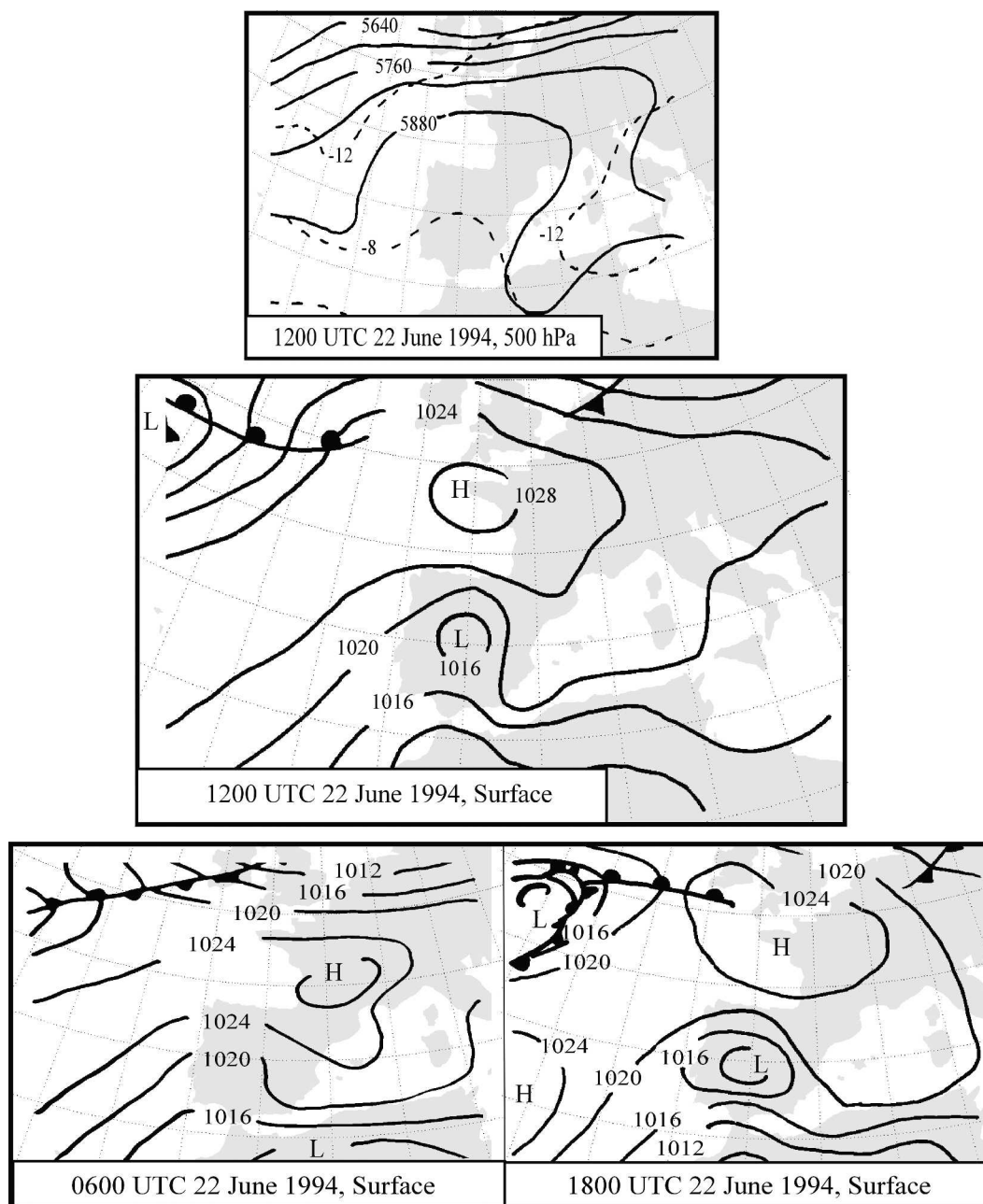


FIG. 5. Development of the ITL on 22 Jun 1994.

these advections to be examples of “backdoor (cold) fronts” (Hushke 1959; Bluestein 1993) and, accordingly, this term will be used in the present work.

4. Mesometeorology of Valencian precipitation

a. Precipitation from frontal systems

The last orographic barrier encountered by traveling Atlantic depressions and their frontal systems before

moving onto the Mediterranean Sea is the coastal mountains. Except for the cases discussed below, precipitation from these fronts occurs mainly on the windward (west) side of these mountains and is followed by a föhn-type effect over the Spanish east coast (Millán et al. 1998). The resulting winds are locally known as “Ponientes,” that is, from where the sun sets. The observed precipitation patterns show significant values at the stations facing inland, that is, on the west side of the

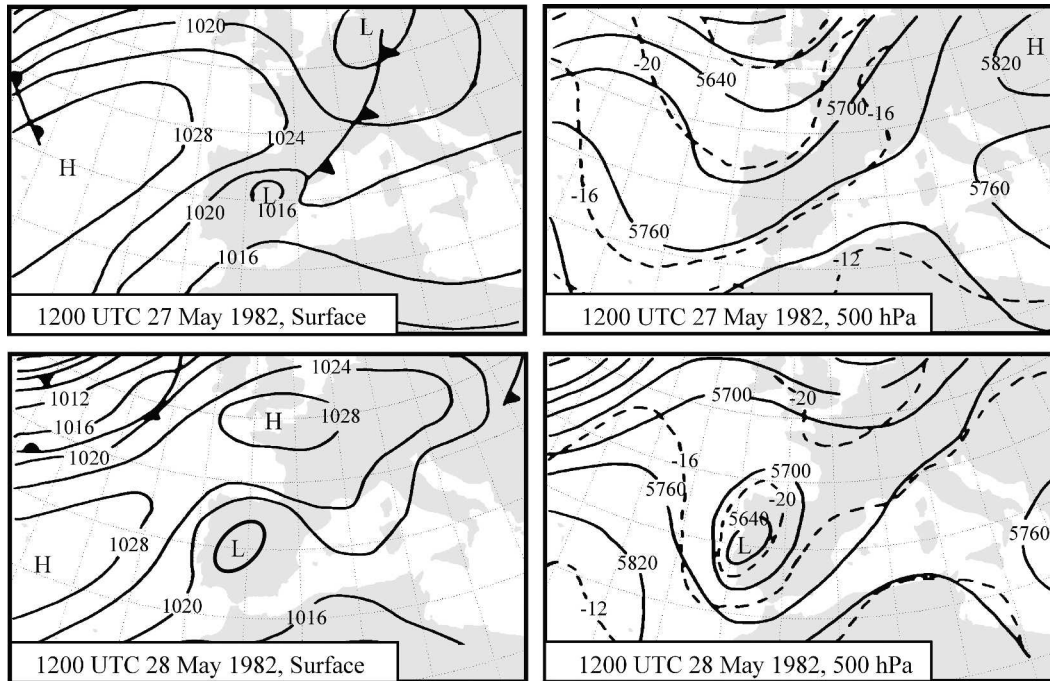


FIG. 6. Development of the ITL on 27 and 28 May 1982, with the formation of an upper trough (pool of cold air aloft).

coastal mountain ridges, and little or no precipitation at the stations on the coastal side. The criterion selected to disaggregate this component from the daily precipitation data is the passage of a frontal system during the rain event, as illustrated in Fig. 4.

b. Convective–orographic (summer) storms

In this region, summer storms are associated with the final stages of development of the combined sea breeze/upslope winds, and they tend to form on the east-facing

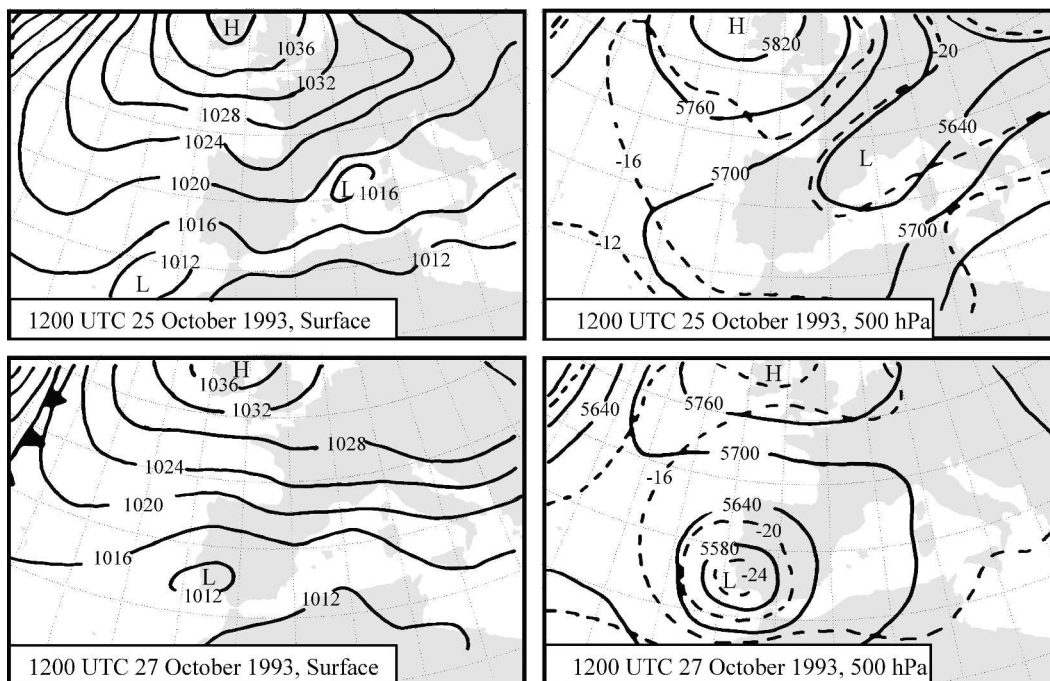


FIG. 7. Evolution of the synoptic conditions during the torrential rain event of 25–27 Oct 1993.

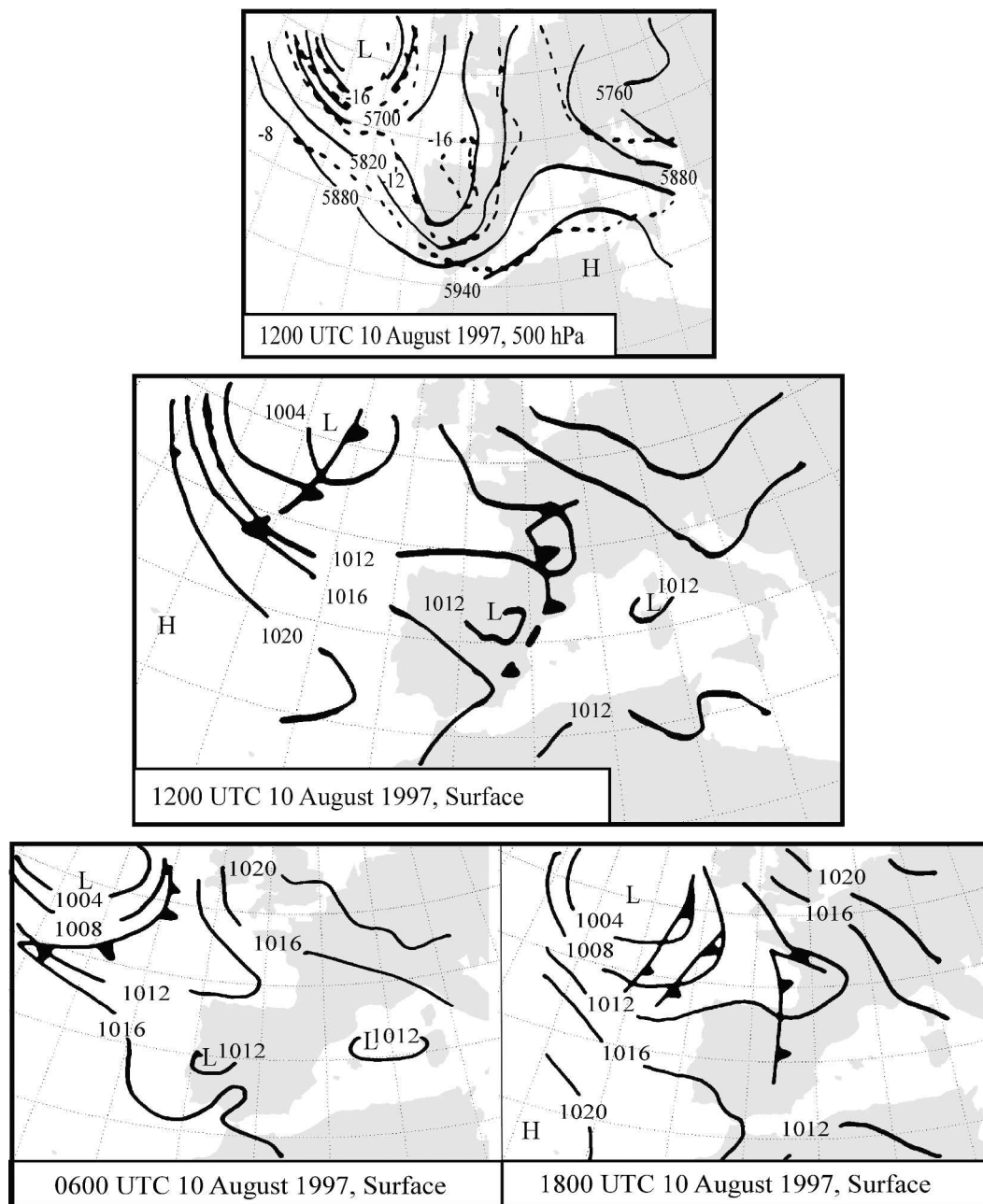


FIG. 8. Synoptic conditions resulting in intense precipitation on 10 Aug 1997. Note the presence of the ITL at 1200 UTC on the day of the event and the advection of Atlantic air while a combined breeze still developed along the Mediterranean coast.

slopes of the coastal mountain ranges in mid- to late afternoon. The sea breeze brings moisture evaporated over the Mediterranean Sea, and additional moisture is provided by evaporation and evapotranspiration along the path of the combined breeze. For a storm to develop, this process has to overcome both the dry(er) air incorporated by the (converging) surface flows on the inland side of the coastal circulations (illustrated in

Figs. 2 and 3), as well as the anticyclonic subsidence that tends to inhibit the vertical development of the convection.

The maturing of storms at the front line of the coastal circulations is favored by the presence of colder air aloft. Furthermore, if a large pool of colder air aloft forms, the storms tend to become more generalized, mature earlier in the afternoon, and can also recur for

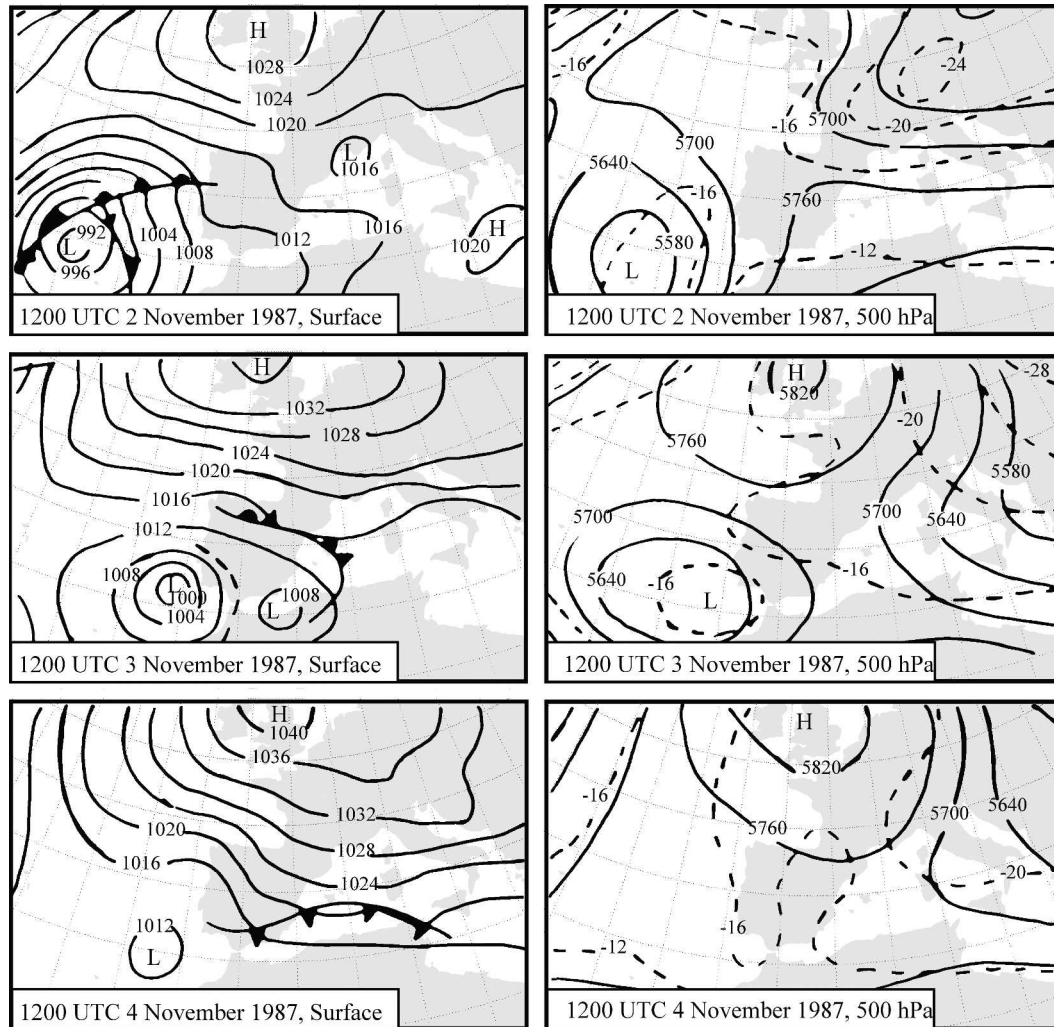


FIG. 9. Synoptic evolution during the torrential event of 4 Nov 1987. It combines the effects of a cutoff low southwest of Spain with easterly advection over the Mediterranean Sea.

several consecutive days. Figure 5 illustrates the synoptic conditions that favor the development of isolated summer storms, and Fig. 6 shows how a pool of cold air aloft (upper trough) develops over the surface thermal low propitiating the development of generalized storms.

In either case, once the storms mature over the east-facing slopes of the coastal mountains, they become coupled to the upper (300 hPa, westerly) flow and are driven eastward, that is, toward the coast, before dissipating during the evening and night. The observed precipitation pattern shows low or nonappreciable values on the west side of the coastal mountains, significant to large values (10 to 30 mm) on the east side, and a sharply decreasing gradient toward the coast. This precipitation component occurs under conditions that favor the formation of the Iberian thermal low on surface

weather maps at either 1200 and/or 1800 UTC (Fig. 5), and thus the presence of the ITL is the criterion selected to disaggregate this component from the daily precipitation data. The presence of colder air aloft (500 to 300 hPa, as shown in Fig. 6) is an additional check.

c. Intense precipitation in late summer and autumn

This includes precipitation of the backdoor (cold) front type, discussed above, which can generate torrential rain on the Spanish east coast. Because of its association with easterly advection, that is, air from the Mediterranean Sea, it is known locally as “Temporal de Levante” (i.e., bad weather coming from where the sun rises) or as “Levanter” in English literature (Hushke 1959). Its development can be reinforced when a cold air pool aloft moves over the Iberian Peninsula from

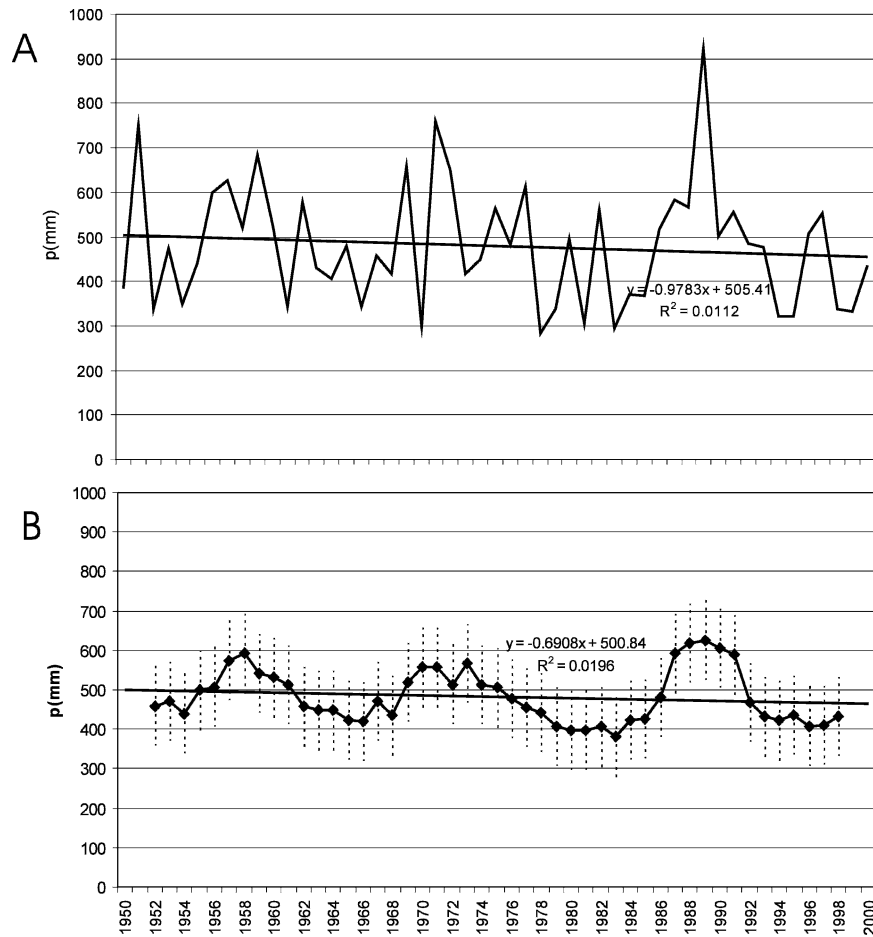


FIG. 10. Area-averaged precipitation and 5-yr running average for the whole Valencia region and adjacent areas for the period 1950–2001.

more northerly latitudes. It can also lead to the formation of a cutoff low over the Atlantic [see section 4d(2) below], producing more generalized precipitation. The observed precipitation patterns include high precipitation values near the coast that diminish toward the interior.

The criterion selected to disaggregate this precipitation component was that an anticyclone must have been present over, or in transit toward, central Europe for a few days previous to the event. In the example shown in Fig. 7, anticyclone migration began on 22 October 1993, the precipitation maximum occurred on the night of 25/26 October, and the event ended on 27 October, that is, when a pool of cold air aloft had become consolidated over the Iberian Peninsula.

d. Mixed situations

There are two other situations that yield significant amounts of precipitation in the Valencia region.

1) CONVERGENCE OF SEA BREEZES AND FRONTS

This type can occur in mid- to late summer, whenever an Atlantic depression drops in latitude and reaches the Iberian Peninsula from the west while the combined breeze continues to develop along the eastern coast and mountain ranges. In these conditions, moist air masses of Atlantic and Mediterranean origin converge over the mountains west and west-southwest of the city of Valencia, where the Iberian Cordillera system is both narrowest and lowest.

This situation (illustrated in Fig. 8) can result in the development of large storms. Once formed, these storms tend to migrate toward the coast during the night. Their precipitation pattern shows high values on both sides of the ridges and decreasing values toward the coast. Sometimes the resulting wetter surface on the coastal side tends to inhibit breeze development on the following day, and thus one feature of these events is that they are short lived, sometimes lasting only one

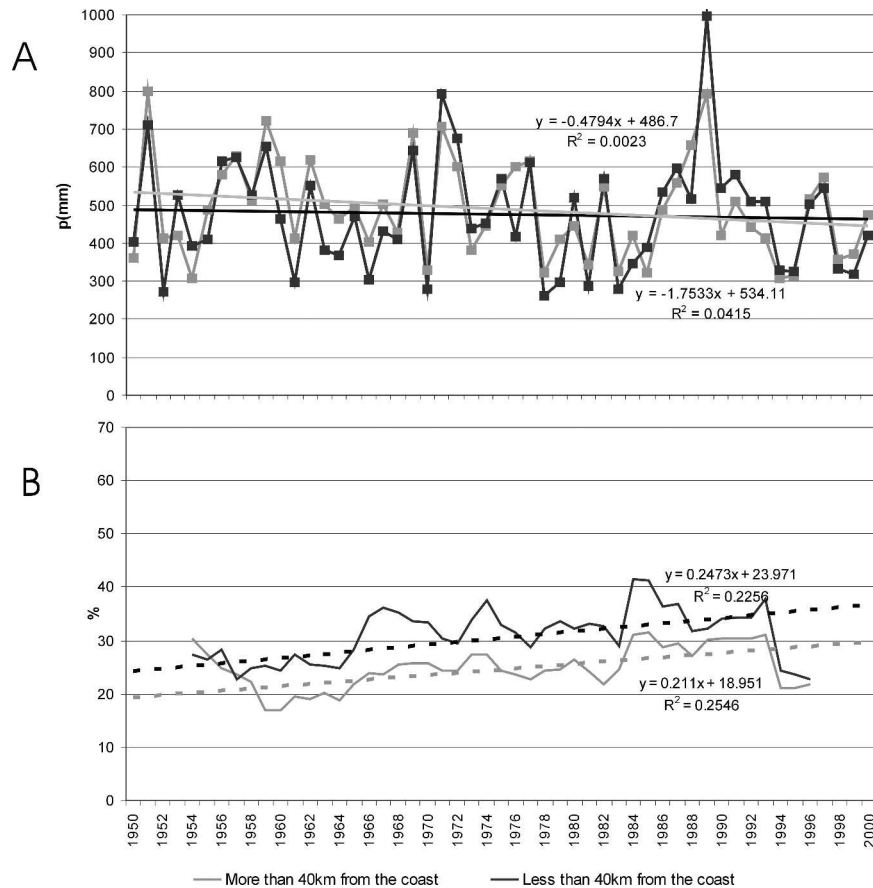


FIG. 11. (a) Area-averaged precipitation series and regression lines for stations located at <40 km from the coast and at ≥ 40 km from the coast. (b) Linear regression and variation coefficient, calculated from the 10-yr running average, for the same series.

evening. Furthermore, on the following day, westerly winds may dominate over the Mediterranean coast (Millán et al. 1998).

These cases combine characteristics of both the summer storm and the frontal precipitation types, including the formation of a weak thermal low at surface level and the presence of colder air and westerly winds aloft. Because westerly advection of Atlantic air is present both on the surface (albeit weak) and on the 500-hPa weather maps, the precipitation collected is assigned to the frontal category.

2) ATLANTIC CUTOFF DEPRESSIONS WITH EASTERLY ADVECTION IN THE MEDITERRANEAN

The key element in these precipitation events is the presence of a central European anticyclone that drives an easterly flow against the Spanish east coast with long marine fetch over the Mediterranean Sea. The resulting precipitation can be reinforced, however, by the

presence and/or development of a cutoff low southwest of the peninsula, and Fig. 9 shows a sequence of synoptic maps illustrating a development of this type. The cutoff low can either dissipate over the Gulf of Cadiz (as illustrated in Fig. 9) or move east along a corridor that includes Gibraltar, the Alboran Sea, and North Africa before dissipating, or becoming reactivated, when it reaches the western Mediterranean basin.

In the latter case, the easterly surface flows over the Valencia region change direction, that is, veering first to the north and then backing toward the south, and the areas affected by the precipitation also change. Initially, the rain falls on the south-facing slopes of the Pre-Betico system north of Alicante. In fact, this is the only situation that yields important rainfall amounts in this area. As the depression moves farther east, the precipitation affects areas farther to the north and may reach Catalonia and the south of France. Finally, as the low dissipates or moves farther east; the last area affected by the precipitation is the north-facing slopes of the

TABLE 1. Precipitation types and disaggregating criteria used.

Precipitation component	Characteristics	Disaggregating criteria
Classic (Atlantic) fronts	Their most frequent occurrence is from early autumn to late spring. Also included is the convergence of westerly Atlantic flows with Mediterranean sea breezes along the coastal mountain ridges in spring and late summer.	Collected rain amounts are assigned to this category whenever a clearly noticeable frontal passage over the Iberian Peninsula has occurred during the precipitation event. Additionally, westerly advection with a cold trough at the 500-hPa level is also considered.
Convective–orographic (summer) storms	This category includes the storms driven by the combined sea breeze and upslope winds. They tend to develop during the afternoon on the sea side of the coastal mountain ranges, some 60–80 km inland, and are more frequent from late Apr to Sep. During the late evening and night these storms migrate easterly (toward the coast) before dissipating.	Rain amounts are attributed to this category whenever the ITL is observed at 1200 and/or 1800 UTC on the day of the event. Additionally, the 500-hPa level is checked for the presence of cold air aloft.
Backdoor (cold) fronts (Levanders)	Events associated with the easterly advection of continental air over a warmer Mediterranean Sea. They occur mainly in autumn and winter and less frequently in spring. They can be very intense, last from 2 to 4 days, and affect mainly areas on the coast and near mountain slopes. If a cutoff low develops southwest of the Iberian Peninsula, the precipitation can become more generalized and last longer (i.e., of the order of 1 week).	To be in this category, the precipitation event has to coincide with the migration and establishment of an anticyclone over central Europe. This can be accompanied, but is not necessarily limited, by the displacement of a cold pool of air aloft toward the Iberian Peninsula and/or by the full development of a cutoff low southwest of the peninsula that may be followed by its migration to the western Mediterranean basin.

Pre-Betico Mountains, that is, the wet nucleus south of Valencia.

The precipitation in this case tends to be much more generalized and long-lasting than in the situation discussed in section 4c; it also tends to affect the whole region. Modeling of these processes (Pastor et al. 2001) indicates that most of the moisture required to drive the precipitation is evaporated from the Mediterranean, and thus the presence of the central European anticyclone, driving easterly advection over the western Mediterranean basin, is considered the main criterion to disaggregate this contribution from the daily precipitation data.

5. Disaggregation of precipitation data by synoptic type

a. Available data and preliminary statistics

The data used for this study are from the Spanish Instituto Nacional de Meteorología (INM) network. The database for this work includes daily precipitation records (0700–0700 UTC) from 1950 to 2000 for 497 stations in the Valencia region and neighboring areas, as shown in Fig. 1. Of these stations, 60 have climatologically homogeneous records (i.e., continuous data for ≥ 30 yr) since 1950, and another 250 stations cover the last 30 yr (to 2000).

The analysis in section 4 [and the results in sections 5b(1)–(3)], indicate that the precipitation in some nearby areas, that is, on one side or the other of the same mountain range and just a few kilometers away, could be dominated by a different precipitation type. And thus, vicinity between stations may not be a guarantee of statistical–climatological continuity in the observations. Therefore, to avoid crossover of relevant information between sites (and possibly between precipitation types), no attempt has been made to complete any gaps in the available data by using data from neighboring stations.

The area-averaged precipitation series for this region, henceforth the primary series, is shown in Fig. 10a. The value plotted for each year is the total precipitation collected divided by the number of reporting stations that year. The linear regression shows a decreasing trend and, in spite of a significant increase in the number of stations over the years, the average series becomes more spiky toward the end; that is, the distribution has a clear positive skewness (see section 6 below). The 5-yr running average for the same series, shown in Fig. 10b, smooths out the individual peaks but suggests a deepening of the main cycles with the maxima increasing and the minima decreasing during the period considered.

A first complementary picture emerges when the pri-

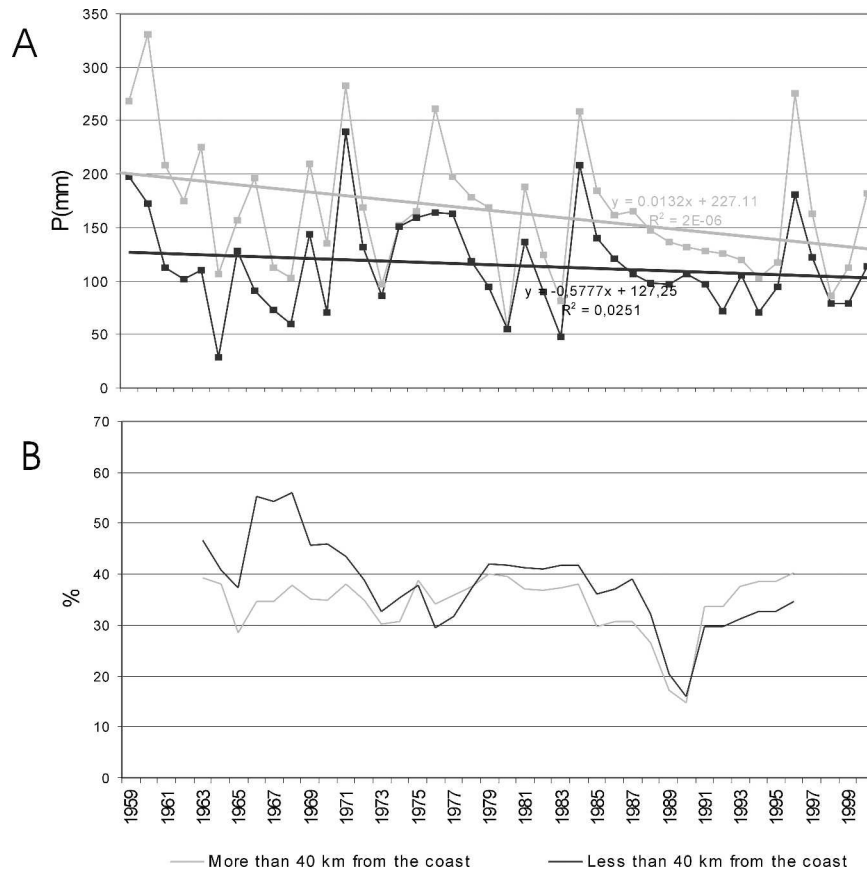


FIG. 12. Precipitation from Atlantic fronts. (a) Area-averaged precipitation series and regression lines for the same two station subsets. (b) Linear regression and variation coefficients for the same two series.

mary series is split on the basis of the distance from the station to the coast (Fig. 11). The 40-km value was selected because it marks approximately both the centerline of the region and the 400-m altitude. A moderately decreasing trend can be observed for inland precipitations (about 30 mm below average in the period 1950–2000). In contrast, total precipitation remains practically invariable on the coast. The coefficient of variation in Fig. 11b tends to increase in a similar way for both the coast and the interior. This confirms previous results (Almarza 2002; Chazarra and Almarza 2002) that show a trend toward more irregular precipitation throughout the region with a notable difference between the amounts collected in the interior and at the coast.

b. Data disaggregation procedure and results

Our next step was to disaggregate the precipitation data by synoptic types to study the evolution of each component. Table 1 presents a summary of the meso-

meteorological analysis and the criteria selected to disaggregate the components from the daily precipitation series. However, because of difficulties in finding appropriate weather maps for Spain before 1959, the synoptic classification had to be limited to the years 1959–2000.

For each day of this 43-yr period, the surface pressure maps at 0000, 0600, 1200, and 1800 UTC, together with the 500- and 300-hPa levels at 1200 UTC, were analyzed, and the precipitation data for that day were assigned to the corresponding synoptic type. The disaggregated precipitation series were further split for the stations near the coast (<40 km inland) and for the stations farther inland (≥ 40 km from the coast).

Finally, to plot the average spatial distribution for each precipitation type, two additional site-specific conditions were applied to the available data, namely, 1) the site must have uninterrupted reporting for at least 30 yr within the period 1959–2000, and 2) the data capture days must be better than 96% for each year within the reporting period; that is, a site with

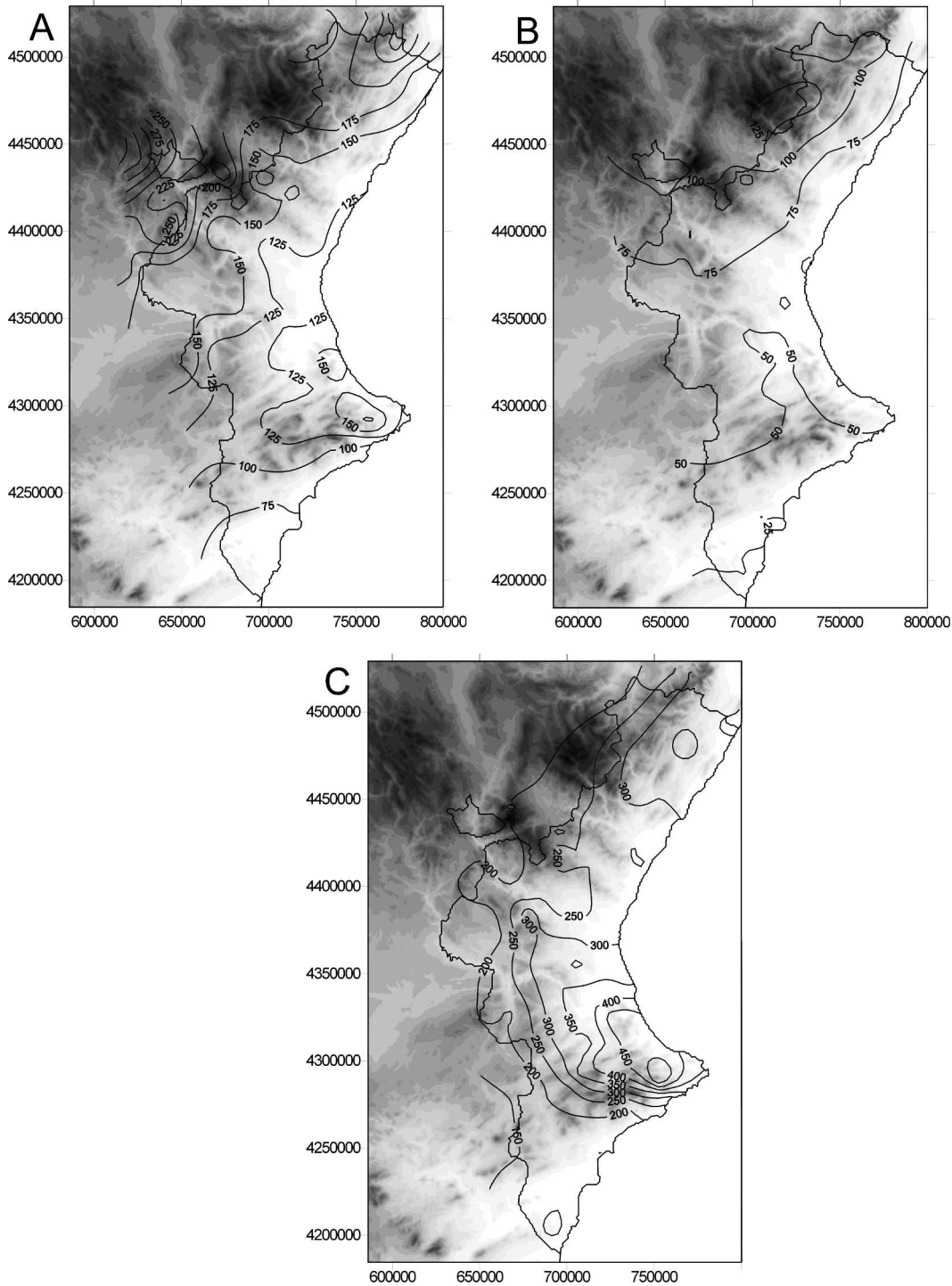


FIG. 13. Spatial distribution of precipitation from (a) Atlantic fronts, (b) convective–orographic summer storms, and (c) backdoor cold fronts.

an accumulated interruption period of more than 14 days in any year was rejected. Only 123 stations fulfilled these conditions and were used for this purpose.

1) FRONTAL PRECIPITATION

The series corresponding to precipitation from Atlantic fronts in Fig. 12a shows a clear decreasing trend

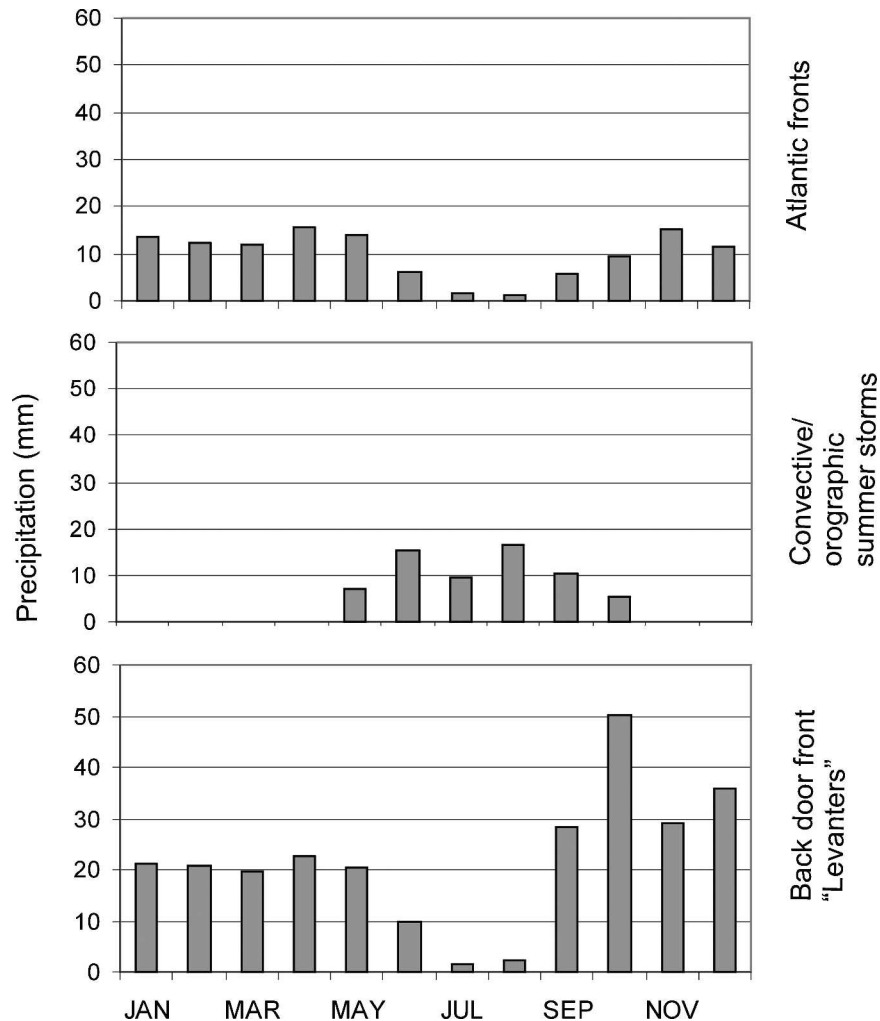


FIG. 14. Monthly precipitation, in mm, from (a) Atlantic fronts, (b) convective–orographic summer storms, and (c) backdoor cold fronts. The values shown are averages for the whole area and for the period 1959–2000.

in annual total precipitation volumes for both the interior and the coast. This trend is more pronounced in the inland areas, registering losses of approximately 25%. The coefficient of variation in Fig. 12b shows a decrease for both series with less irregularity inland than on the coast.

The spatial distribution for this component is shown in Fig. 13a, and its monthly variation is shown in Fig. 14a. As previously discussed (sections 3a and 4a), the contributions from frontal systems are relatively insignificant on the coast and increase with distance inland. The highest values are registered over the southwest-facing (i.e., inland-facing) slopes of the Iberian Mountains at the northwestern edges of the region, where they exceed 275 mm of annual rainfall and account for as much as 45% of the total precipitation in those areas. In the south of the region, they provide less than 75 mm

of the annual average rainfall (less than 20% of total precipitation).

2) CONVECTIVE–OROGRAPHIC (SUMMER) STORMS

The series for convective–orographic storms appears in Fig. 15a. It also shows a decreasing trend for this component both in the interior and on the coast. The decreases are more moderate though, ranging from less than 10% on the coast to 18% inland. The coefficient of variation in Fig. 15b shows a clear increasing trend.

The spatial distribution in Fig. 13b confirms the observations mentioned in section 4b and shows a maximum over the Iberian Mountains inland, albeit over the Mediterranean-facing side. Convective–orographic storms generate a substantial amount of precipitation in these areas, that is, an average of 100–125 mm yearly.

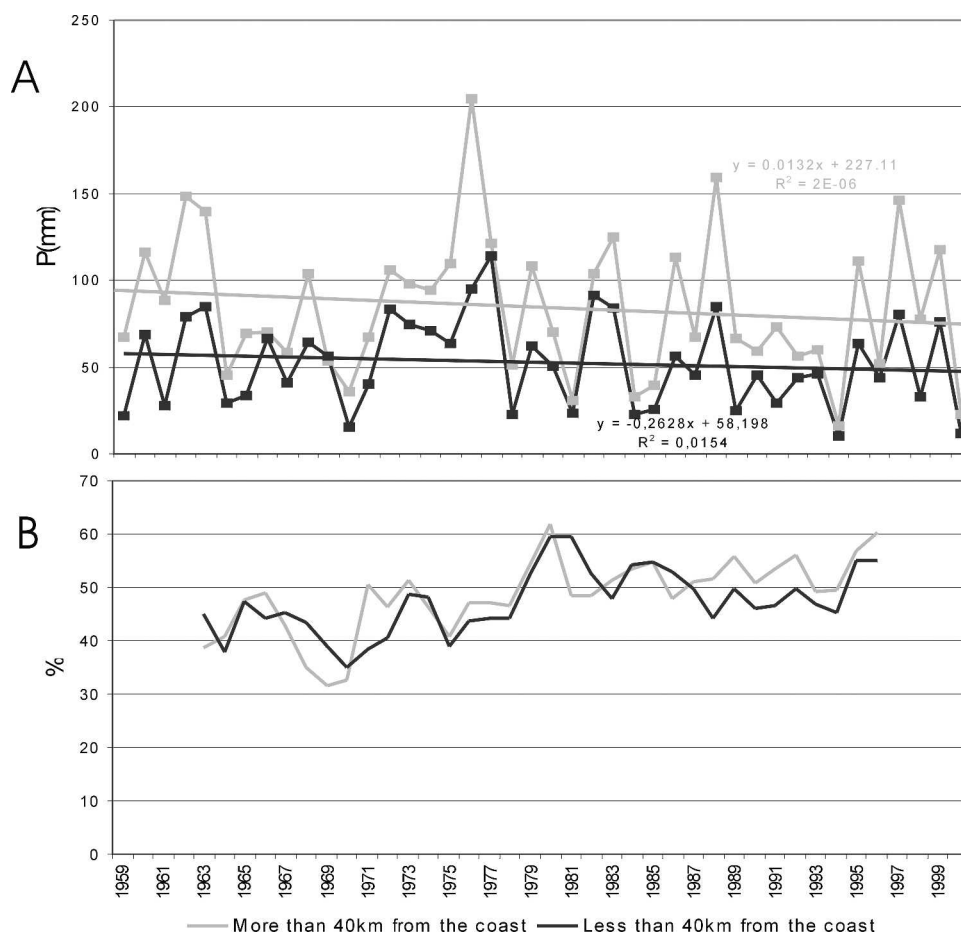


FIG. 15. Precipitation from convective–orographic summer storms. (a) Area-averaged precipitation series and regression lines for the two station subsets. (b) Linear regression and variation coefficients.

This component generally diminishes toward the coast and toward the south of the region, where it contributes only 10% of the total precipitation. Finally, Fig. 14b shows its monthly variation.

3) LEVANTERS: EASTERLY ADVECTION OVER THE MEDITERRANEAN

The series for the backdoor (cold) fronts (Fig. 16a) shows an opposite trend to the other precipitation components, that is, toward increasing annual totals on the coast and maintaining previous levels in the interior. In fact, the increased rainfall at the coast explains why the average precipitation remains unchanged for this part of the study area. An interesting aspect of this synoptic type is its interannual behavior. The evolution in the coefficient of variation, in Fig. 16b, shows an increasing trend that declined in the 1990s after a very intense peak in the mid-1980s.

The spatial distribution of this component also confirms field observations (section 4c) and is shown in Fig.

13c. The largest rainfall amounts occur near the coast and decrease toward the interior, that is, basically the opposite of that of the frontal systems. Precipitation events from backdoor cold fronts are very important not only in the wet nucleus (Valencia: south; Alicante: north) where they contribute over 450 mm, but also in the arid zone farther south where, with an average of 150 mm yr^{-1} , they represent more than 65% of the total precipitation. The monthly distribution is shown in Fig. 14c.

6. Complementary statistics and correlations

a. Statistics for the 1959–79 and 1980–2000 intervals

It was suggested, during review, that the series be subdivided into two intervals and any relevant differences evaluated. Thus, Fig. 17 shows the monthly precipitation values for the disaggregated series, for the intervals 1959–79 and 1980–2000. These amounts can be compared with those for the full period (Fig. 14).

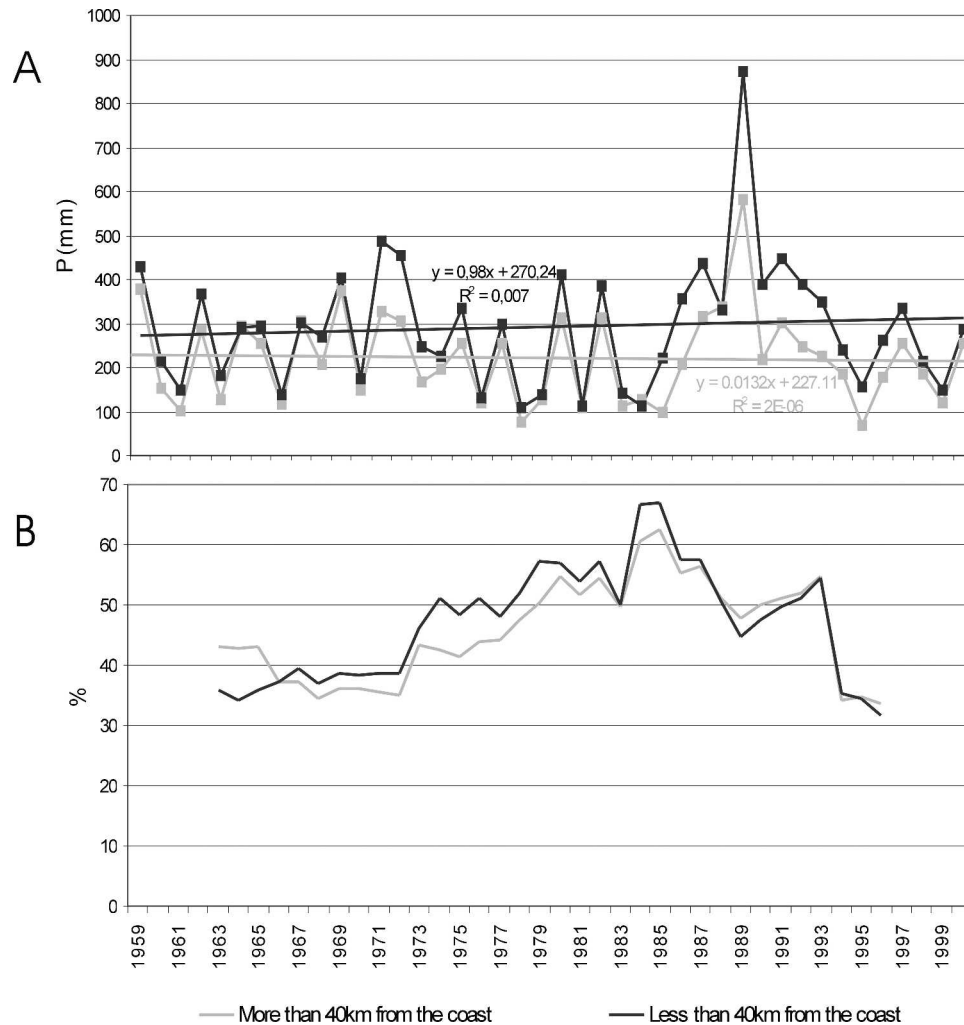


FIG. 16. Same as in Fig. 15, but from backdoor cold fronts/Levanteers/Mediterranean cyclogenesis.

In the second interval, the contribution from the frontal systems decreases, and the summer storm periods shift toward the autumn. However, the most obvious difference between the two subseries is the increase in precipitation from backdoor (cold) fronts, which show a tendency to increase in autumn and, particularly, in winter–spring. This is also reflected in the change in the number of major events shown in Table 2.

Moreover, Fig. 18 shows the decadal variation in the collected precipitation volumes. These graphs show a moderate and persistent reduction in small and medium values, that is, below 30 mm, during the whole period. On the other hand, the contribution from >125-mm events, which are generally related to backdoor (cold) fronts, shows a decreasing trend during the first three decades (i.e., roughly during the first interval) and a pronounced increase after 1980, that

is, large enough to influence the series and yield an average increasing trend for the whole period. The questions raised are discussed in section 7 below.

Table 3 shows the skewness and kurtosis for the primary series and for both subintervals. The skewness increases both for the average subseries and for the disaggregated components (as mentioned in section 5a). The changes are more pronounced for the backdoor (cold) front components and less so for the components from the Atlantic fronts. These statistics also confirm the trends shown in Fig. 18. The data suggest that precipitation on the Spanish east coast is becoming more intense in nature and concentrated in fewer days per year, and per decade, thus confirming the hypothesis of an increase in both inter- and intra-annual irregularity. It also appears that the more extreme (torrential) events, related to backdoor (cold)

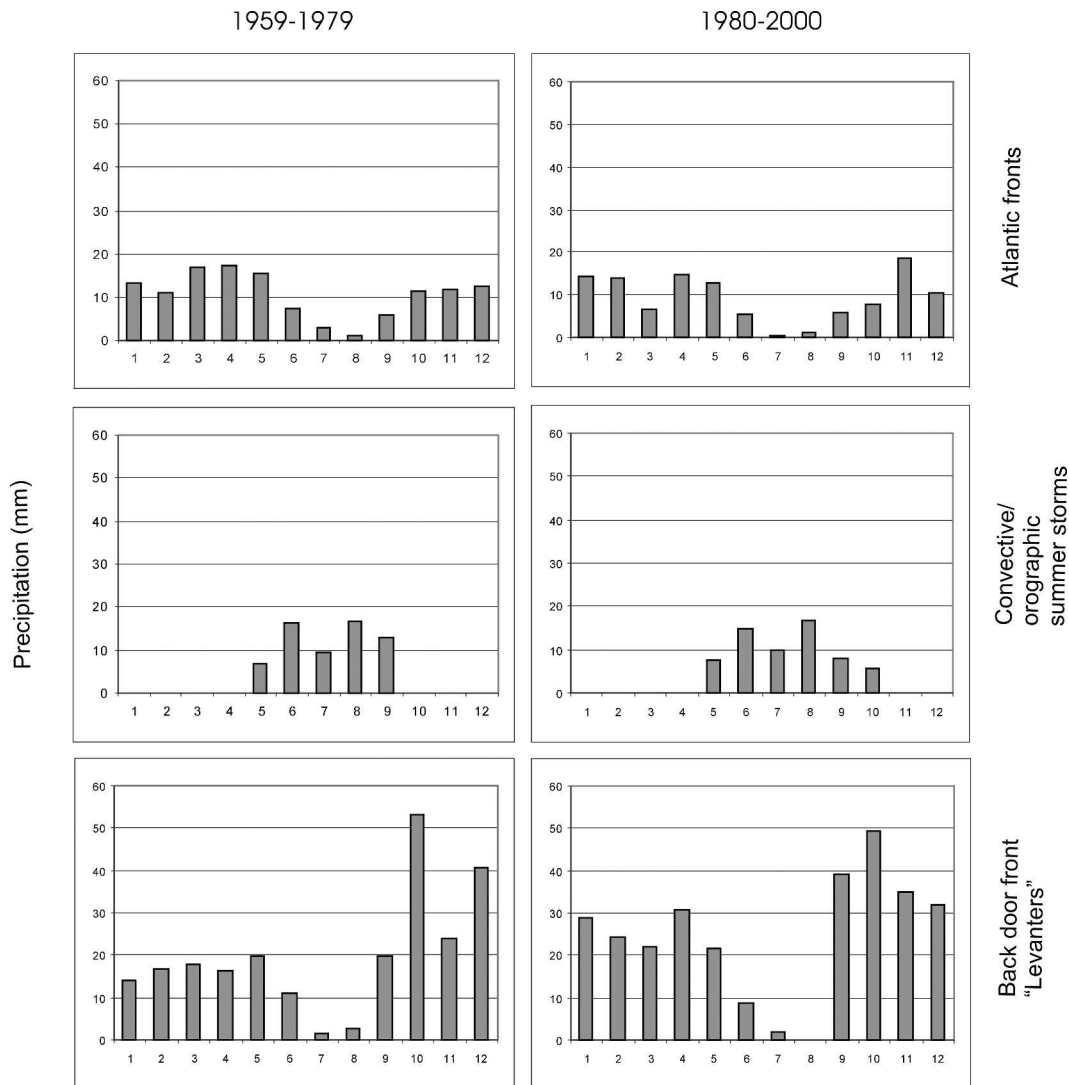


FIG. 17. Same as in Fig. 14, but left column shows area averages for the interval 1959–79, and right column shows area averages for 1980–2000.

fronts (Levanter), are increasing in the first semester of the year (winter and spring), in contrast to their more “normal” (older) tendency to reach their maxima in autumn.

TABLE 2. Number of major events associated with backdoor (cold) fronts (Levanter).

Threshold	Intervals	No. of events	
		First semester	Second semester
>125 mm	1950–79	8	51
	1980–2000	19	58
>150 mm	1950–79	2	35
	1980–2000	9	40

b. Correlations with the North Atlantic Oscillation index

The series for the full 1959–2000 period have been correlated with the annual, winter, and summer NAO indexes and with the 5-yr running averages of the annual index. Both the Azores–Iceland (A–I; more information available online at www.cgd.ucar.edu/cas/jhurrell/indices.data.html naostat) and the Gibraltar–Iceland (G–I; more information available online at www.cru.uea.ac.uk/cru/data/nao.htm) series were used, and Table 4 shows the results for the latter. In principle, no significant correlation was found between the NAO annual index and the primary series (including all sites and conditions).

This situation changes when the disaggregated com-

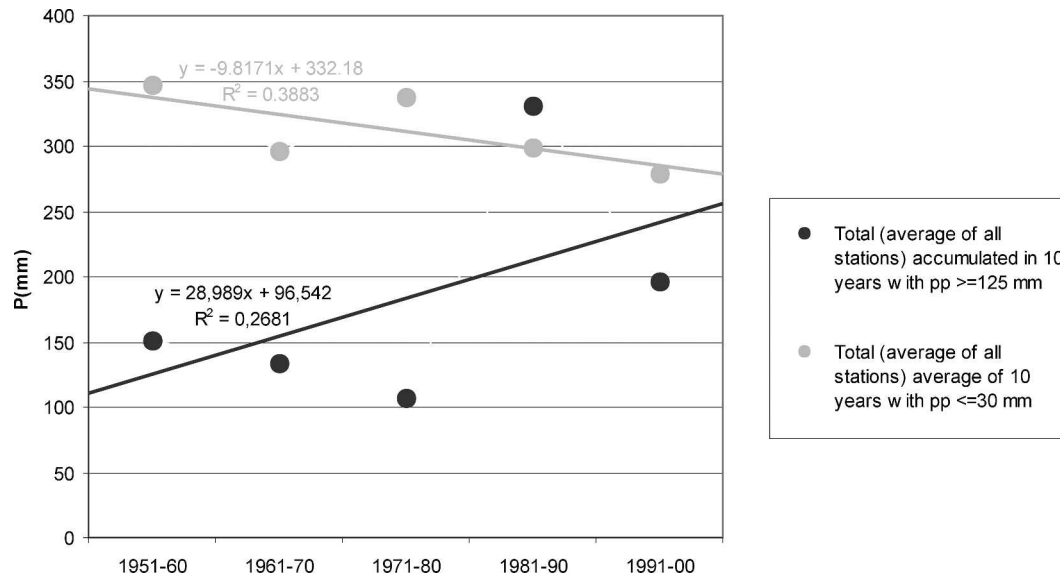


FIG. 18. Decadal variation in average total-accumulated precipitation for thresholds: ≤ 30 and ≥ 125 mm day $^{-1}$.

ponents are used. The NAO winter index is anticorrelated with the frontal precipitations inland, yielding in fact the largest negative value obtained; these rainfalls, in turn, are more directly linked to Atlantic weather phenomena. Likewise, the correlation coefficients for the summer storm component are also negative, but the values are lower and also have less statistical significance for either the inland or the coastal series.

The opposite occurs with the precipitation from backdoor (cold) fronts (Levantes). In this case, the correlations are positive, and the best correlation is obtained with the NAO 5-yr running average for both the coastal (with the largest value) and the inland series. As discussed in section 4, these rains require the presence of a blocking anticyclone over Europe, and the rains

affect mostly the coastal areas. Figure 19 shows graphically the relations between the NAO (G–I) index 5-yr running average and each precipitation component.

7. Conclusions

The results of this work reveal a trend toward reduced precipitation totals in the Valencia region, although this generalization masks important differences related to precipitation type and station placement. For the three types of synoptic situations determined—Atlantic frontal systems, summer convective–orographic storms, and backdoor (cold) fronts—a tendency toward changing precipitation patterns is observed both in the interior and on the coast. In the interior, there has been

TABLE 3. Skewness and kurtosis for the primary and disaggregated series.

Primary series												
		Coast				Inland						
		Skewness		Kurtosis		Skewness		Kurtosis				
1959–79		3.6		18.7		3.3		22.3				
1980–2000		7.8		120.2		4.1		27.2				
Disaggregated components												
Atlantic fronts					Summer storms				Backdoor cold fronts			
Coast		Inland		Coast		Inland		Coast		Inland		
Skewness	Kurtosis	Skewness	Kurtosis	Skewness	Kurtosis	Skewness	kurtosis	Skewness	Kurtosis	Skewness	Kurtosis	
1959–79	3.9	26.7	2.1	6.7	2.6	8.7	2.1	7.6	2.5	8.7	3.2	18.3
1980–2000	3.4	16.5	3.6	22.4	3.1	13.7	2.9	15.5	5.9	60.9	3.5	16.6

TABLE 4. Correlation of primary and disaggregated series with NAO Gibraltar–Iceland index (G–I).

Data series type	Correlation coefficient pp-NAO (Pearson)	Confidence interval (95% if value <0.05)	Correlation coefficient pp-NAO (Spearman)	Confidence interval (95% if value <0.05)	
INDEX					
Primary (all sites and conditions)	−0.04	0.79	−0.11	0.49	NAO annual
>40 km inland and all conditions	−0.12	0.44	−0.16	0.33	NAO annual
<40 km from coast and all conditions	0	0.99	−0.06	0.69	NAO annual
Atlantic fronts/coast	−0.25	0.11	−0.23	0.15	NAO annual
Atlantic fronts/inland	−0.28	0.07	−0.29	0.06	NAO annual
Atlantic fronts/coast	−0.34	0.03	−0.31	0.048	NAO winter
Atlantic fronts/inland	−0.61	0.000 01	−0.59	0.000 05	NAO winter
Atlantic fronts/coast	−0.25	0.13	−0.19	0.25	NAO 5-yr running avg
Atlantic fronts/inland	−0.36	0.03	−0.32	0.047	NAO 5-yr running avg
Summer storms/coast	−0.24	0.13	−0.26	0.10	NAO annual
Summer storms/inland	−0.17	0.29	−0.17	0.27	NAO annual
Summer storms/coast	−0.24	0.13	−0.23	0.15	NAO summer
Summer storms/inland	−0.15	0.34	−0.20	0.20	NAO summer
Summer storms/coast	−0.25	0.14	−0.13	0.45	NAO 5-yr running avg
Summer storms/inland	−0.11	0.50	0.01	0.95	NAO 5-yr running avg
Backdoor fronts/coast	0.12	0.46	0.04	0.81	NAO annual
Backdoor fronts /inland	0.09	0.58	0.03	0.85	NAO annual
Backdoor fronts/coast	0.04	0.25	−0.05	0.74	NAO winter
Backdoor fronts /inland	−0.07	0.65	−0.13	0.41	NAO winter
Backdoor fronts/coast	0.47	0.002	0.13	0.44	NAO 5-yr running avg
Backdoor fronts /inland	0.34	0.04	0.09	0.58	NAO 5-yr running avg

a reduction in overall precipitation volumes from both summer storms and Atlantic fronts. In contrast, the coastal area of the region has registered an increase in precipitation derived from backdoor (cold) fronts, with a concomitant increase in the collected volumes as well as a tendency for greater irregularity.

The evolution of the coefficient of variation for the backdoor (cold) front contribution (Fig. 16b) shows an increasing trend that declined in the 1990s after a very intense peak in the 1980s. If this occurs because the oscillations for this type of precipitation take place over periods of several years, the following questions arise: are large events increasing in magnitude, and are they recurring over longer periods? Here we are faced with the need for longer series to make a better evaluation of trends.

From our analysis we can conclude the following.

- There has been a decrease in the precipitation corresponding to the lowest thresholds, that is, that related to Atlantic fronts and convective situations. This type of precipitation occurs mainly inland and is more effective for the hydrological system.
- There has been an increase in the precipitation corresponding to the highest thresholds (>125 mm), that is, that related to backdoor (cold) front situations. This type of precipitation is less effective for the hy-

drological system because of its more coastal location and its torrentiality leading to floods.

With the available data, however, we cannot state that these trends are a consequence of climate change nor that they respond to the NAO in a unique way. The negative correlation with frontal precipitation of Atlantic origin is in line with other results (Hurrell 1995; Marshall et al. 2001; Mariotti et al. 2002a), while the positive correlation with the backdoor (cold) front contribution (albeit for the 5-yr running average series) would tend to confirm that strong European anticyclones (in autumn–winter) reinforce this type of process (i.e., Mediterranean cyclogenesis).

Additionally, recent works by Marshall et al. (2004a,b) in Florida indicate that anthropogenic land-use perturbations play a significant role in areas subject to mesometeorological processes with diurnal cycle, like the Mediterranean area (see section 3b), and Pastor et al. (2001) have shown that precipitation from backdoor cold fronts in the western Mediterranean basin increases with a warmer sea.

All of these indicate 1) that precipitation in the Mediterranean basin occurs as a result of different (meteorological) processes, 2) that any correlations of precipitation amounts with large-scale indexes (like NAO) should properly consider station(s) location(s) and re-

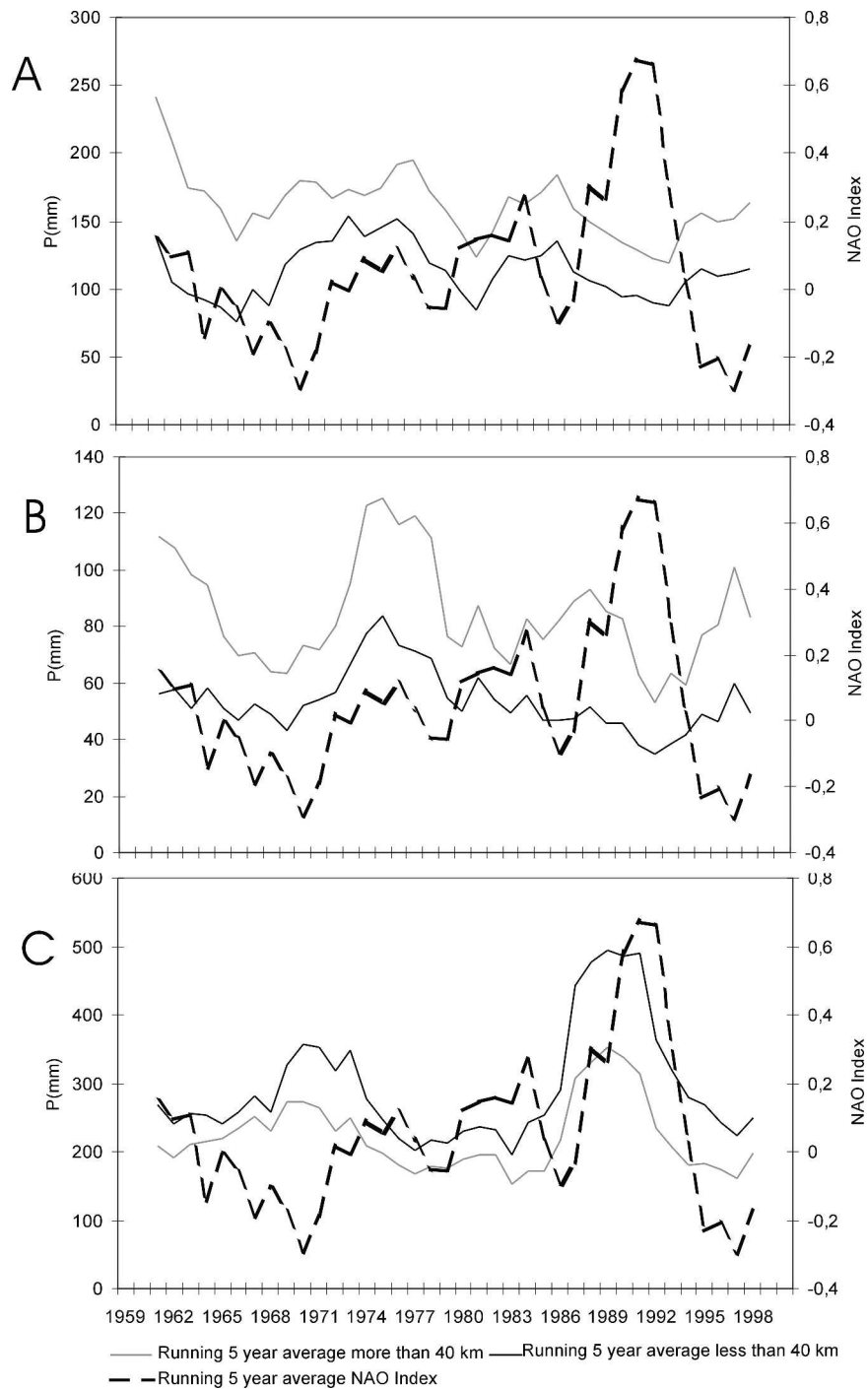


FIG. 19. Comparison between the 5-yr running average of the NAO index and the precipitation components from (a) Atlantic fronts, (b) convective-orographic summer storms, and (c) backdoor cold fronts.

sponse to precipitation types, and 3) that other mechanisms, for example, cumulative heating of the sea surface through feedbacks, could also play an important role in perturbing the precipitation regime in these subtropical latitudes (Millán et al. 2005).

Finally, with this work we would like to point out that if the observed trends continue, the impacts for our region in the medium term will become serious and will exacerbate the drought conditions even if the annual precipitation totals stay within present amounts.

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